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Renewable and Sustainable Energy Reviews
10 (2006) 1–23

RENEWABLE
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ENERGY REVIEWS

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# Prospects of solar water heating for textile industry in Pakistan

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Received 6 July 2004; accepted 23 July 2004

**Abstract**

Energy is the prime source of human activities in all sectors of life. Traditionally fossil fuel has been the prime source of energy. However, there are two major concerns regarding fossil fuels, i.e. their rapid depletion and their contribution towards growing global warming. It is being widely realized that for sustainable development presently used energy mediums such as fossil fuel and nuclear power have to be quickly replaced by renewable energy sources. The latter are sustainable and have the potential to meet present and future projected global energy demands without inflicting any environmental impacts.

Pakistan is amongst the most prominent cotton producing countries in the world. The affluent availability of local cotton has lead to a well-established textile sector in Pakistan. A large proportion of its cotton products go into export. Being a successful candidate in international textile market Pakistani textile industry is continuously seeking modern and high-tech facilities to improve quality of its products. The biggest challenge Pakistani textile industry is facing today is how to cut down its environmental burdens to cope with the international standards on the issue.

Water heating system as required for dying process is one of the major energy consuming areas in fossil fuel-run Pakistani textile industry. Water heating system therefore has a significant contribution towards total environmental impacts associated with textile sector.

This work presents an alternate, sustainable solution for water heating by means of fossil fuel. It has been shown herein that under Pakistan's climate solar energy can contribute significantly towards this duty. In the present work two different designs of built-in storage water heater—plain and newly designed finned type—were constructed to compare their thermal performance. Three months of experimental data were collected for the two heaters. The solar fractions for this period

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1364-0321/$ - see front matter 
doi:10.1016/j.rser.2004.07.003

were found to be 63 and 73%, respectively. The monetary and embodied energy payback periods for the two heaters were, respectively, found to be 6.7 and 6.1 years, and 185 and 169 days.


*Keywords:* Solar energy; Textile industry; Heaters

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## 1. Introduction

Energy is the backbone of human activities. The importance of energy in economic development is also very critical as there is a strong relationship between energy and economic activity. Historically fossil fuel in its solid phase, i.e. wood and coal has been the prime source of energy. The increment in energy global demands due to population growth and 19th century industrial revolution, lead fossil fuel through a transitional phase. World saw their refined liquid phase, oil that is more efficient than wood and coal. More recently world became familiarised with gaseous phase of fossil fuels that is even more efficient. Renewable energy sources such as biomass have also been utilised since the beginning of civilisation. By the middle of 20th century, the developed countries to meet their energy needs introduced nuclear power.

The depletion of fossil fuels which contribute to 80% of world's primary energy supply, and environmental impacts associated with presently used energy modes have emphasised the need for an alternate solution to meet global energy needs without inflicting any serious environmental impacts. Renewable energy sources are the answer to these energy and environmental challenges. Renewables such as solar, wind, hydropower and biogas are potential candidates to meet global energy requirements in a sustainable way. Solar energy has the potential, not only, to play an important role in providing most of the heating, cooling and electricity needs of the world, but also to solve global environmental problems. The most wide spread thermal use of solar energy, so far, has been for water heating. Solar water heating systems have been commercialized in many counties in the world. Integrated collector/storage solar water heaters, also called built-in-storage heaters, due to their simple and compact structure offer a promising approach for solar water heating in colder climates. One of the potential areas of application of such heater is in textile industry where large amount of hot water is required in dyeing process.

Pakistan is not only an energy deficient country but is also facing serious threats caused by the global warming. Pakistan, for example, which has a coast extending over approximately a thousand kilometres, is one of the countries classified by United Nations Environment Program (UNEP) through its OCA/PAC regional seas program, as being particularly vulnerable to the effects of sea level rise. The country's largest city, Karachi, which houses almost 10% of the total population, and about 40% of all manufacturing units, is situated on the coast [1].

Textile industry in Pakistan is facing the challenge of tackling its environmental impacts to cope with the international standards. There are hardly any textile industries in Pakistan that have addressed the issue. The present work proposes solar energy as an alternate energy source to meet the hot water requirements in textile sector. This will not only contribute to energy needs but also reduce the associated environmental impacts.

The present work aimed to study the prospects of built-in-storage water heaters within the Pakistani textile industry. An innovative design has been adopted that is the introduction of fins to improve its thermal performance and structural stability. The authors using technology available within Pakistan constructed both of the presently discussed heater designs—plain type and the one presently introduced, i.e. finned type heater. Both heaters were operated on a parallel basis. Three months of performance data have been gathered to compare their performance. Results are provided in this article.

## 2. Global energy and environmental scene

Fossil fuels are the most important source of world's present primary energy supply. Fossil fuels reserves are, however, diminishing rapidly across the world, intensifying the stress on existing reserves day-by-day due to increased demand. Fossil fuels, presently contributing to 80% of world primary energy, are inflicting enormous impacts on the environment. Climatic changes driven by human activities, in particular the production of Greenhouse Gas emissions (GHG), directly impact the environment. According to World Health Organisation (WHO) as many as 160,000 people die each year from the side effects of climate change and the numbers could almost double by 2020. These side effects range

from malaria to malnutrition and diarrhoea that follow in the wake of floods, droughts and warmer temperatures. Another example of the severe impact caused by the global warming is the heat wave that hit across the Europe in summer of 2003 causing deaths in tens of thousands [2].

Climate change is responsible for huge economical consequences. Between the 1960s and the 1990s, the number of significant natural catastrophes such as floods and storms rose nine-fold, and the associated economic losses rose by a factor of nine. Figures indicate that the economical losses as a direct result of natural catastrophes over 5 years between 1954 and 1959 were US$35 billion while between 1995 and 1999 these losses were around US$340 billion [3]. Europe's extreme summer heat wave was the biggest single event in the year 2003—costing more than $10 billion in agricultural losses alone and killing some 20,000 people [4].

Energy sector has a key role in this regard since energy during its production, distribution and consumption is responsible for producing environmentally harmful substances. A secure and accessible supply of energy is thus very crucial for the sustainability of modern societies. There is an urgent need for a quicker switch over of energy systems from conventional to renewables that are sustainable and can meet the present and projected world energy demand.

## 3. Geographical and other information for Pakistan

Pakistan lies in southern Asia, bordering the Arabian Sea, between India on the east and Iran and Afghanistan on the west and China in the north. Pakistan lies between 23.8 and 36.7°N latitude and 61.1 and 75.8°E longitude, and has a total area of 803,940 $km^2$ of which 97% is land area while rest is covered by water. The country is characterized by significant variations in altitude and topography across its territory. Pakistan's diversity extends to its climatic, socio-economic, and environmental characteristics, which differ significantly from region-to-region. Pakistan's coastline with the Arabian Sea stretches to over 990 km. Pakistan with a population of about 140 million, which is expected to rise to 210 million by 2025, is the eighth most populous country in the world. Pakistan has four provinces, the Punjab, the North West Frontier Province (NWFP), Sindh, Balochistan, and two federally administrated territories: the Federally Administered Tribal Areas (FATA) and the Northern Areas. In addition, the territory of Azad Jammu and Kashmir (AJK), is under the administration of the Government of Pakistan. Pakistan's per capita GDP is US$2000 while the three main sectors: industry, agriculture, and services, constitute a GDP share of 26.6, 25.2, and 48.2%, respectively. Main industries include textiles, and apparel, food processing, beverages, construction materials, paper products, fertilizer and other agricultural products [1,5,6].

Table 1 shows the sectorial breakdown of energy consumption for Pakistan. Fig. 1 shows the climatic zones for Pakistan including contours of annual-mean daily solar irradiation. It is clear that in the cold north and northwest regions of the country there is a case for solar water heating even for the domestic sector. The figure also shows that the solar radiation budget is quite healthy throughout the country (Table 1).

Table 1
Pakistan's energy consumption by sector (units = GW h)

| Sector | 1999–2000 | |
|---|---|---|
| | Units | % |
| Total | 46,358 | 100.0 |
| Domestic | 21,485 | 46.4 |
| Commercial | 2544 | 5.5 |
| Industrial | 13,972 | 30.1 |
| Agricultural | 4542 | 9.8 |
| Public lighting | 239 | 0.5 |
| Bulk supply | 3576 | 7.7 |

Tables 2 and 3, respectively, present information on the solar irradiation measurement network and the historically recorded monthly mean solar irradiation. Note that except Quetta, all other stations have now ceased solar irradiation measurements.

### 3.1. Energy demand and solar potential

Pakistan like other developing countries is energy deficient—the demand for primary energy in Pakistan has increased considerably over the last decades and the country is

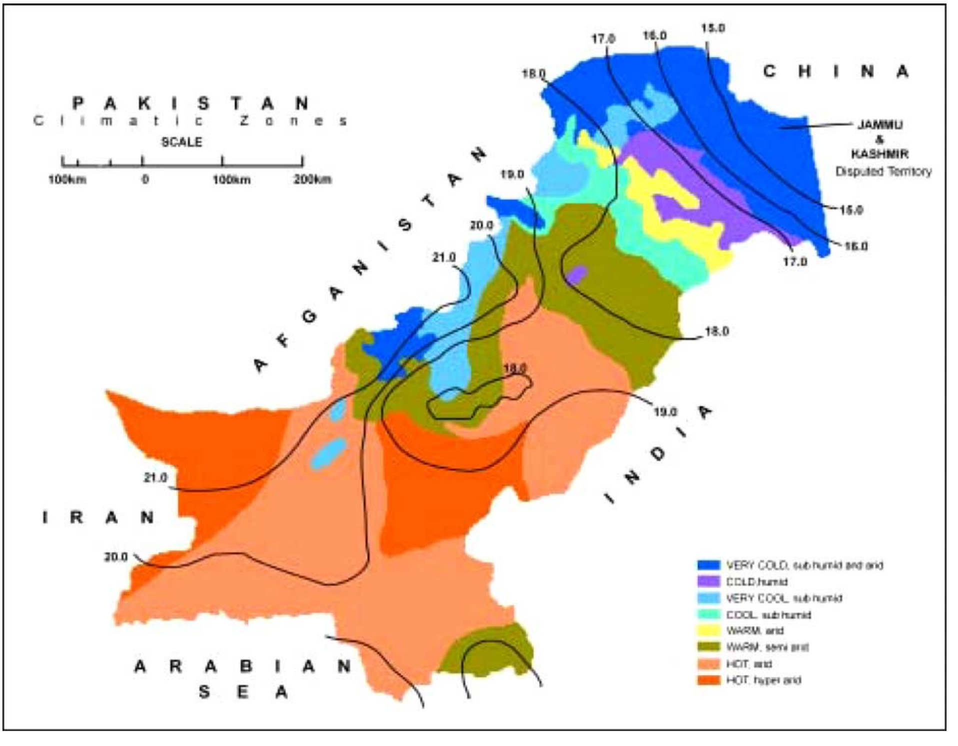



Fig. 1. Climatic zones for Pakistan including isoflux contours of annual-mean daily solar irradiation, MJ/m$^2$ day.

Table 2
Irradiation measuring stations in Pakistan

| Station | Latitude | Longitude | Elevation (m) | Period |
|---|---|---|---|---|
| Islamabad | 33.72°N | 73.10°E | 510 | 1985 |
| Karachi | 24.90°N | 67.13°E | 21 | 1975–1989 |
| Lahore | 31.55°N | 74.33°E | 213 | 1975–1989 |
| Multan | 30.20°N | 71.43°E | 122 | 1975–1989 |
| Peshawar | 34.00°N | 71.52°E | 358 | 1975–1981 |
| Quetta | 30.18°N | 66.95°E | 1672 | 1975–1989 |

facing serious energy shortage problems The conventional energy resources, oil, gas and coal, are limited and hence the domestic production does not keep in pace with the increase in demand. Pakistan still accounts for only 0.5% of the world's total energy consumption although its energy consumption has nearly trebled during the last 20 years. Despite this three-fold increase in installed electricity generation capacity, less than half of the house-holds are electrified and per capita electricity supply is only 443 kW h per year against 12,500 kW h in the USA and 7500 kW h in Japan [7]. Main source of energy in Pakistan is fossil fuel that meets 63% of the total energy demands of the country. Hydropower is the second largest energy source that presently meets 36% of energy needs. Nuclear power shares the remaining 1% of the total energy needs. Total primary energy supplies measured in terms of tonnes of oil equivalent (TOE) in 2002–2003 were 47.1 million.

Pakistan has vast potential for renewable energy development: the three provinces of Pakistan, i.e. NWFP, Balochistan and Sindh provide vast untapped resources for hydropower, wind and solar energy. The geographical location, topography and local climate of the country favour the exploitation of these resources. Pakistan is ideally located in the sunny belt to take advantage of solar energy technologies. This energy source is widely distributed and abundantly available in the country. The province of Balochistan is particularly rich in solar energy having one of the highest values of annual mean sunshine duration. The energy sector is the single largest source of greenhouse gas emissions as detailed in the inventory developed for Pakistan. As such, it is also the sector, which is believed to have the greatest potential for development of mitigation options.

### *3.2. The textile industry in Pakistan*

The local textile industry has been the backbone of Pakistan's economy. It contributes more than 60% to the total export earnings of the country, accounts for 46% of the total manufacturing and provides employment to 38% of the manufacturing labour force. The availability of basic raw material for textile industry, cotton, has played a principal role in the growth of the industry. Pakistan is the world's fourth largest producer and consumer of cotton. Most of the Pakistan's textile trade is with USA, EU and the Middle East. The main textile exports include cotton cloth, cotton yarn, knitwear, tents, and canvas/tarpaulin, silk and synthetic textile. According to All Pakistan Textile Manufacturer Association (APTMA), the US is the biggest trading partner of Pakistan and in the year 2002/2003, the volume of two-way trade stood at $2.43 billion, followed by EU states with annual trade

Table 3
Irradiation values for Pakistan, MJ/m$^2$ day

| Month | Karachi | | | Multan | | | Quetta | | | Lahore | | | Islamabad | | | Peshawar | | | Benghazi, Libya, average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Average | Min. | Max. | Average | Min. | Max. | Average | Min. | Max. | Average | Min. | Max. | Average | Min. | Max. | Average | |
| January | 9.6 | 17.7 | 15.3 | 6.0 | 15.2 | 12.2 | 5.9 | 17.6 | 13.2 | 4.6 | 14.2 | 10.5 | 4.6 | 14.1 | 10.1 | 4.4 | 15.6 | 10.5 | 11.2 |
| February | 10.0 | 19.8 | 16.3 | 6.9 | 18.8 | 14.6 | 7.4 | 21.7 | 16.0 | 5.7 | 19.1 | 13.8 | 4.4 | 17.5 | 13.6 | 5.3 | 19.9 | 14.3 | 13.0 |
| March | 11.0 | 23.7 | 20.2 | 8.8 | 23.2 | 18.0 | 9.0 | 25.1 | 18.9 | 7.6 | 23.4 | 17.6 | 5.7 | 21.9 | 15.5 | 5.8 | 24.8 | 17.4 | 16.6 |
| April | 15.9 | 25.0 | 22.2 | 13.5 | 26.2 | 22.5 | 12.9 | 29.6 | 24.2 | 10.8 | 26.0 | 21.6 | 9.7 | 27.2 | 22.0 | 10.4 | 28.0 | 21.5 | 20.2 |
| May | 17.0 | 26.4 | 23.0 | 13.9 | 27.4 | 23.6 | 15.0 | 32.1 | 27.4 | 12.4 | 27.7 | 23.1 | 13.0 | 28.1 | 24.3 | 13.2 | 30.1 | 24.9 | 24.1 |
| June | 14.2 | 27.4 | 22.5 | 13.2 | 27.1 | 22.8 | 21.2 | 32.0 | 28.6 | 12.8 | 28.0 | 23.6 | 13.5 | 28.0 | 23.3 | 16.5 | 31.2 | 26.5 | 24.1 |
| July | 10.4 | 25.6 | 17.5 | 12.4 | 26.3 | 21.6 | 15.2 | 29.6 | 24.9 | 8.4 | 26.5 | 18.9 | 10.8 | 27.3 | 21.1 | 12.6 | 28.7 | 23.2 | 26.3 |
| August | 9.8 | 25.6 | 16.8 | 13.5 | 25.3 | 21.4 | 14.8 | 27.6 | 24.1 | 9.4 | 25.9 | 19.5 | 10.1 | 25.3 | 20.5 | 9.1 | 26.2 | 20.9 | 24.1 |
| September | 11.6 | 24.6 | 30.1 | 14.1 | 23.2 | 20.2 | 17.9 | 26.1 | 23.1 | 11.9 | 23.7 | 19.8 | 13.4 | 2.1 | 19.5 | 3.2 | 23.4 | 19.2 | 19.4 |
| October | 14.2 | 21.4 | 18.9 | 11.9 | 19.6 | 16.7 | 13.7 | 22.9 | 19.7 | 10.6 | 19.2 | 16.0 | 8.9 | 18.4 | 15.7 | 9.1 | 19.2 | 16.0 | 14.8 |
| November | 11.5 | 18.1 | 15.7 | 9.6 | 15.9 | 14.0 | 8.6 | 18.8 | 15.3 | 7.2 | 15.0 | 12.4 | 7.8 | 14.5 | 11.6 | 7.0 | 16.7 | 16.3 | 12.2 |
| December | 8.2 | 15.8 | 14.1 | 5.9 | 13.6 | 11.1 | 0.2 | 15.2 | 12.3 | 4.7 | 13.1 | 10.2 | 3.8 | 11.7 | 8.1 | 4.6 | 13.1 | 10.5 | 43.2 |

volume of around $2.4 billion. Pakistan currently exports a total of $1.9 billion worth of apparel and textiles annually to the United States and is the fourth largest supplier of these goods [8].

Pakistani textile industry is facing a tough challenge in the form of global environmental standards. To sustain its role in export markets, Pakistan has to comply with international environmental protocols. Pakistan Agricultural Research Council has warned that Pakistan's textile exports face a bleak prospect in the coming years unless the government adopts focussed measures to address the concerns relating to environment and updating of technology [9]. In fossil fuel-run textile units, toxic emissions into the air and ground water are the major environmental concerns. In the post January 2005 quota free market scenario, it will be inevitable to implement quality standards such as ISO 9001 and environmental standard ISO 14000. It is therefore very important for the textile industry to adopt environmentally efficient technologies to address any future challenges.

## 4. Solar water heating

### 4.1. Thermosyphon and built-in-storage water heaters—a comparison

Thermosyphon systems, as shown in Fig. 2, use the natural tendency of heated water to rise and cooler water to fall to perform the heat collection task. As the sun shines on the collector, the water inside the collector flow-tubes is heated. As it heats, this water expands slightly and becomes lighter than the cold water in the solar storage tank mounted above the collector. Gravity then pulls heavier, cold water down from the tank and into the collector inlet. The cold water pushes the heated water through the collector outlet and into the top of the tank, thus heating the water in the tank.

'Built in storage water heater' combines flat-plate collector and storage tank in one unit. The built-in-storage heart possesses several advantages over the thermosyphonic type. These are as follows: higher efficiency owing to the fact that firstly, no thermal losses occur while water is flowing through connecting pipes, and secondly owing to no loss of efficiency due to poor bond conductance (between the plate and tubes of a collector used in

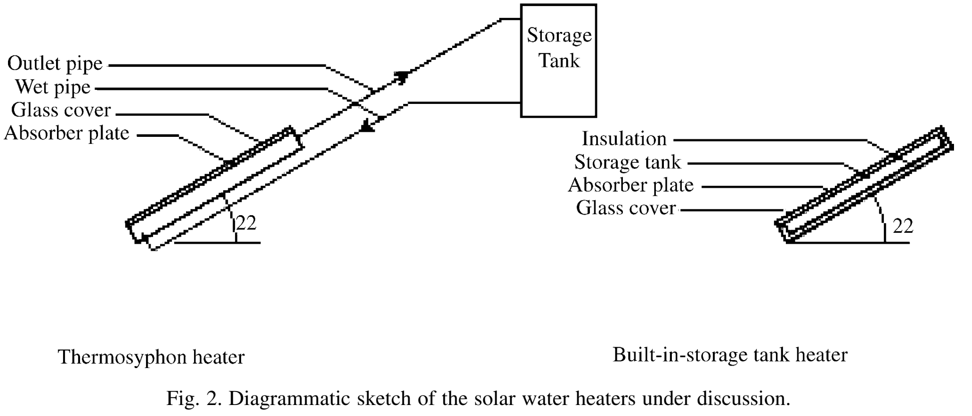



Fig. 2. Diagrammatic sketch of the solar water heaters under discussion.

thermosyphon system) and fin efficiency which may occur in the less expensive flat-plate collectors. Also they are compact in structure, which is not the case with thermosyphon system and is a draw back from the aesthetic standpoint. Moreover built-in-storage heaters are cheaper due to their simplicity of construction.

However, the most severe disadvantage of the built-in-storage water heater is the sharp night cooling from the glass cover resulting in cooler water temperatures in the morning hours. This problem has been attempted to be solved by either covering glass with an insulated cover during the night or by transferring the heated water into a separate insulated drum for storage at the end of the day.

### *4.2. Potential for solar water heating in textile industry*

Like most of other industrial sectors, textile industry requires a continuous supply of water. The major application of water in textile industry is in dyeing process. Water is required not only at normal temperature but also at temperature as high as 80 °C. Heating up water at such a high temperature consumes considerable energy. Water if heated through conventional energy sources consequently has environmental impacts.

Solar water heating is a potential candidate to replace the conventional energy sources in textile industry and can be an economical choice. Adopting this technology can also substantially reduce the environmental impacts.

## 5. Experimental investigation of built-in-storage water heaters (plain and finned types)

The present work proposes the introduction of built-in-storage water heaters for Pakistani textile industry due to its low cost and simple construction as compared to thermosyphon heaters. However, a new design has been adopted within built-in-type heaters by introducing fins within its construction. Fins not only improve the thermal efficiency of the heater but also add to the structural stability of heater—fins joined to the top and bottom layers of heater can provide additional strength against hydrostatic forces and can help overcome the bulging problems that usually arise in such designs. In the present work both of these heater designs—plain and newly designed finned type—were constructed to compare their thermal performance.

### *5.1. Construction*

Plain and finned water heaters that were presently constructed were of the same size and specifications except that the latter was provided with fins. Each of these heaters, being of the built-in-storage type, primarily consisted of a water storage tank, each having dimensions of 1 m×1 m, with a depth of 0.08 m. These tanks were constructed through bending and welding of 1 mm thick stainless steel sheets, which formed the top, bottom and sides. The top surface of the steel boxes was painted with blackboard paint to act as the absorber plate. Water inlet and outlet valves, each of the size of 0.025 m, were, respectively, provided on the side and top of the box. The storage tank needs to be insulated to protect

from convection heat loss. For this purpose, the storage tanks were wrapped with 0.05 m of glass wool insulation on all sides and bottom and housed in an outer wooden box. The top black painted surface of the box was covered with a 4 mm thick glass sheet to maintain an air gap of 0.025 m. The steel assembly was used to mount the heaters at an angle of 22°, this being the optimum angle for maximising the annual solar gain.

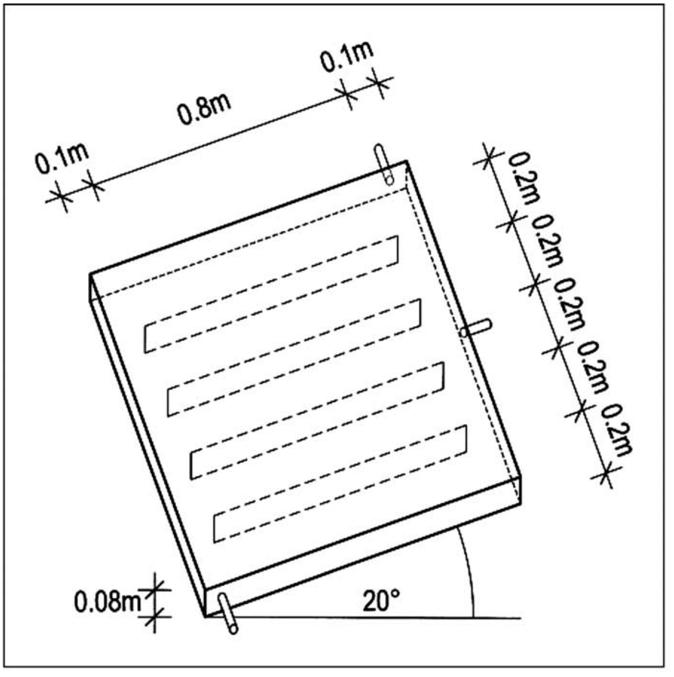
The fins used within the finned heater were made of 1 mm thick stainless steel sheet as used in construction of the heater itself. There were four fins used, each of a length of 0.8 m and of a height of 0.08 m (equal to the depth of the box). These fins were fixed inside the boxes joining the top and bottom surfaces, and parallel to its sides, leaving a distance of 0.1 m from both the top and bottom ends as shown in Fig. 3. The four fins were fixed with a pitch of 0.2 m. Fins were arc welded.

### *5.2. Measurement scheme and data collection*

Both of the above mentioned water heaters, i.e. the built-in-storage plain—as well as the finned heater were fully instrumented to enable the measurement of hourly variation of ambient air and water temperature and its longitudinal stratification. A total of five thermocouples were used to measure the longitudinal temperature stratification within each heater by means of a direct temperature read-out device. The ambient temperature was recorded via thermocouples as well as a Stevenson screen based mercury-in-glass thermometer. Technical staff at the Din Textile Mills, Bhai Pheru (Lahore, Pakistan) maintained a manual record of all experiments, which were then keyed-in within MS-Excel and the electronic files then transferred via email to the present authors in Edinburgh.

It shall be shown herein that a strong stratification effect along the longitudinal axis of either of the two heaters was noticed. This is not surprising as even within the storage tanks of thermosyphon heaters such effects are well known and have been the subject of numerous scientific investigations. However, within the built-in-storage with a lack of bulk circulation, as is the case with the former heater, a much more pronounced stratification is to be expected. Fig. 4 shows one such plot for a clear (May 2, 2004) and an overcast day (May 1, 2004) for the finned heater. Similar temperature profiles were noted for the plain heater, but have not been included for the sake of brevity and in view of the economy of publication space. Note that for the overcast day the lower lamina of water take a much longer time to heat up as compared to the clear day. The cold water introduced within the two heaters at the beginning of the day was drawn from a nearby well and thus, on occasions, has shown a lower temperature than the ambient air temperature.

In view of these stratification effects and bearing in mind that the main purpose of the experiments was to obtain the value of the bulk temperature of the heated water at the days end, on a number of occasions the entire body of heated water was discharged in an insulated drum, the water well stirred and the temperature of the well-mixed water noted. This temperature was found to be close to the reading of the middle thermocouple that was placed at a distance of 580 mm from the top (thermocouple number 2). The bulk temperature profile displayed in the following figures is henceforth represented by the read-out of the latter thermocouple. Table 4 presents measured data for the daily temperature lift by the two heaters for the present measurement period. Furthermore,



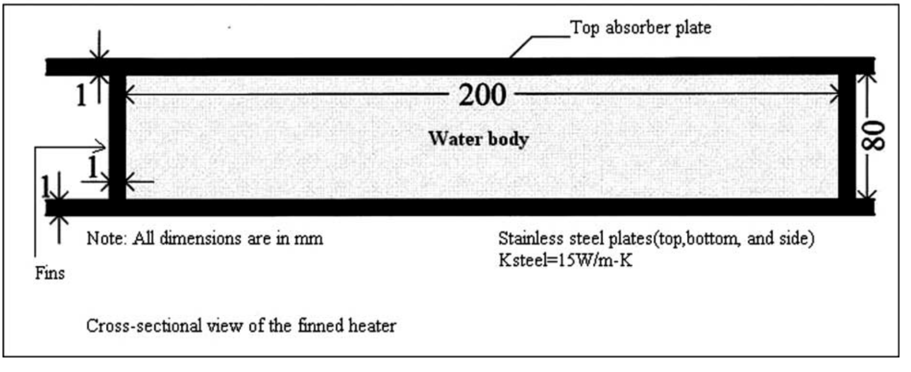




Fig. 3. Isometric (a) and sectional (b) drawing of the finned heater.

Fig. 5 enables a graphical comparison of the hourly temperature profile for the two heaters for a clear and an overcast day. The finned heater demonstrates a significant performance improvement. As a matter of fact the solar fraction of the finned and plain heaters for the present measurement period are, respectively, 73 and 63%. The respective solar contributions are also clearly shown via Fig. 6. In this figure the thick, solid line at the top represents the hot water temperature demand (80 °C). The area between this thick, solid line and the loosely broken line at the very bottom (cold water temperature) represents the total energy consumption. The area between the temperature profile of the hot water delivered by any given heater and the temperature profile of the cold water is proportional to the solar contribution.

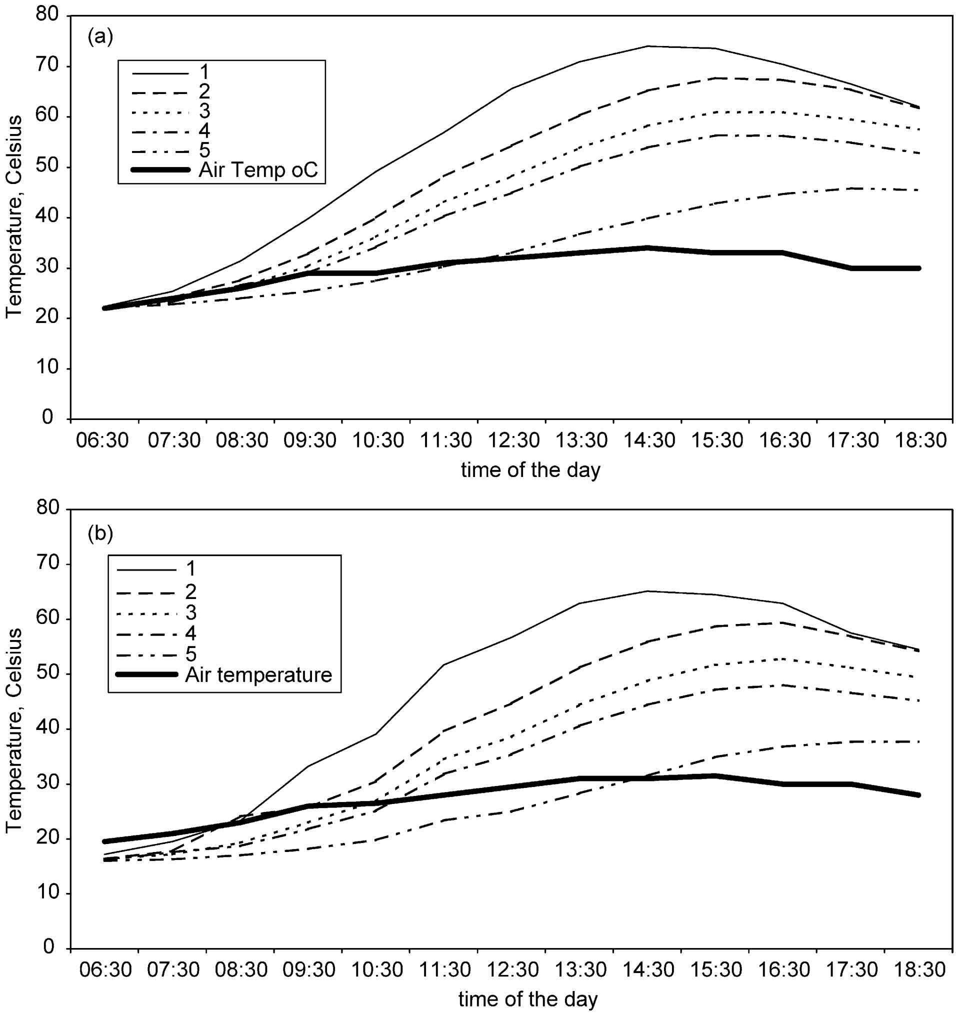



Fig. 4. Temperature distribution in finned heater: (a) clear day (May 2, 2004) and (b) overcast day (May 1, 2004). Temperature of the water body at depths of: (1) 260; (2) 420; (3) 580; (4) 740; and (5) 900 mm.

### 5.3. Analysis

Following from Section 5.2 wherein the enhanced performance of finned as compared to the plain heater was reported, an analysis of the thermal enhancement effect of the fin is now presented. The fin plays a dual role: firstly, it acts as a support for the top, absorber plate and thus avoids the bulging due to hydrostatic pressures exerted by the stored water within the heater. Secondly, the fin attempts to enhance the heat transfer from the absorber plate to the deeper layers of water. Note that within the plain heater the fact that heat is being transferred from a heated plate at the top to a cooler body of water residing underneath is an inefficient convection process. On the other hand, the vertically placed fin

Table 4
Daily cold water inlet and end-of-the-day heated water temperatures

| Date | Cold water temperature (°C) | Hot water temperature (°C) | | Remarks |
|---|---|---|---|---|
| | | Plain heater | Finned heater | |
| 21/04/2004 | 25 | 50 | | No observations available |
| 22/04/2004 | 27 | 40 | | No observations available |
| 23/04/2004 | 20 | 59 | | No observations available |
| 25/04/2004 | 23 | 60 | 67 | No observations available |
| 26/04/2004 | 25 | 60 | 64 | No observations available |
| 27/04/2004 | 28 | 59 | 65 | No observations available |
| 28/04/2004 | 28 | 60 | 67 | No observations available |
| 29/04/2004 | 23 | 52 | 52 | Overcast day |
| 30/04/2004 | 24 | 44 | 44 | Overcast day |
| 01/05/2004 | 19 | 56 | 59 | Overcast day |
| 02/05/2004 | 26 | 64 | 67 | Clear day |
| 03/05/2004 | 26 | 62 | 65 | Clear day |
| 04/05/2004 | 25 | 66 | 70 | Clear day |
| 05/05/2004 | 25 | 63 | 73 | Clear day |
| 06/05/2004 | 26 | 59 | 79 | Clear day |
| 07/05/2004 | 28 | 62 | 72 | Clear day |
| 08/05/2004 | 30 | 61 | 65 | Clear day |
| 09/05/2004 | 30 | 68 | 72 | Clear day |
| 10/05/2004 | 27 | 68 | 73 | Clear day |
| 11/05/2004 | 26 | 64 | 72 | Clear day |
| 13/05/2004 | 29 | 70 | 75 | Clear day |
| 14/05/2004 | 29 | 67 | 73 | Clear day |
| 15/05/2004 | 29 | 66 | 73 | Clear day |
| 16/05/2004 | 30 | 66 | 74 | Clear day |
| 17/05/2004 | 32 | 64 | 73 | Clear day |
| 19/05/2004 | 32 | 70 | 78 | Clear day |
| 20/05/2004 | 30 | 70 | 73 | Clear day |
| 21/05/2004 | 26 | 69 | 73 | Clear day |
| 22/05/2004 | 27 | 63 | 71 | Clear day |
| 23/05/2004 | 32 | 48 | 49 | Clear and windy day |
| 24/05/2004 | 27 | 59 | 64 | Clear day |
| 25/05/2004 | 31 | 64 | 66 | Clear day |
| 26/05/2004 | 27 | 60 | 66 | Clear day |
| 27/05/2004 | 29 | 49 | 54 | Clear day |
| 28/05/2004 | 26 | 62 | 67 | Clear day |
| 29/05/2004 | 26 | 68 | 72 | Clear day |
| 30/05/2004 | 29 | 67 | 72 | Clear day |
| 31/05/2004 | 30 | 62 | 68 | Clear day |
| 04/06/2004 | 29 | 63 | 73 | Clear day |
| 05/06/2004 | 30 | 58 | 73 | Clear day |
| 06/06/2004 | 30 | 63 | 70 | Clear day |
| 07/06/2004 | 26 | 54 | 65 | Forenoon clear, then overcast |
| 08/06/2004 | 28 | 65 | 70 | Clear day |
| 09/06/2004 | 27 | 64 | 68 | Clear day |
| 10/06/2004 | 27 | 60 | 72 | Clear day |

(*continued on next page*)

Table 4 (*continued*)

| Date | Cold water temperature (°C) | Hot water temperature (°C) | | Remarks |
|---|---|---|---|---|
| | | Plain heater | Finned heater | |
| 11/06/2004 | 28 | 64 | 70 | Clear day |
| 16/06/2004 | 28 | 60 | 69 | No observations available |
| 17/06/2004 | 32 | 64 | 68 | Clear day |
| 18/06/2004 | 28 | 62 | 65 | Clear day |
| 19/06/2004 | 31 | 60 | 60 | Rainy day |
| 20/06/2004 | 31 | 55 | 55 | Rainy day |
| 21/06/2004 | 28 | 58 | 60 | Rainy day |
| 22/06/2004 | 28 | 46 | 46 | Rainy day |
| 23/06/2004 | 29 | 54 | 55 | Rainy day |
| 24/06/2004 | 27 | 38 | 37 | Rainy day |
| 25/06/2004 | 25 | 61 | 64 | Rainy day |
| 26/06/2004 | 28 | 66 | 70 | Clear day |
| 27/06/2004 | 29 | 68 | 69 | Clear day |
| 28/06/2004 | 29 | 66 | 71 | Clear day |
| 29/06/2004 | 29 | 59 | 70 | Clear day |
| 30/06/2004 | 30 | 62 | 69 | Clear day |
| 01/07/2004 | 29 | 69 | 71 | Clear day |
| 02/07/2004 | 29 | 68 | 69 | Clear day |
| 03/07/2004 | 29 | 69 | 72 | Clear day |
| 04/07/2004 | 30 | 62 | 68 | Clear day |
| 05/07/2004 | 30 | 56 | 63 | Forenoon clear, then overcast |
| 06/07/2004 | 30 | 61 | 68 | Clear day |
| 07/07/2004 | 31 | 65 | 70 | Clear day |
| 08/07/2004 | 29 | 61 | 62 | Clear day |
| 09/07/2004 | 28 | 55 | 57 | Clear day |
| 10/07/2004 | 29 | 60 | 63 | Clear day |
| 11/07/2004 | 29 | 61 | 64 | Clear day |
| 12/07/2004 | 28 | 59 | 67 | Clear day |
| 13/07/2004 | 30 | 63 | 68 | Clear day |
| 14/07/2004 | 30 | 60 | 64 | Clear day |
| 15/07/2004 | 31 | 62 | 70 | Clear day |
| 16/07/2004 | 32 | 49 | 52 | Forenoon clear, then overcast |
| 19/07/2004 | 28 | 54 | 58 | Forenoon clear, then overcast |
| 20/07/2004 | 28 | 66 | 69 | Forenoon clear, then overcast |
| 21/07/2004 | 25 | 60 | 63 | Clear day |
| 22/07/2004 | 28 | 62 | 66 | Clear day |
| 23/07/2004 | 28 | 66 | 68 | Clear day |
| 24/07/2004 | 30 | 68 | 70 | Clear day |
| 25/07/2004 | 30 | 69 | 73 | Clear day |
| 26/07/2004 | 31 | 64 | 69 | Clear day |
| 01/08/2004 | 27 | 48 | 55 | Overcast day |
| 02/08/2004 | 28 | 53 | 54 | Overcast day |
| 03/08/2004 | 28 | 57 | 58 | Clear day |
| 04/08/2004 | 28 | 54 | 63 | Clear day |
| 05/08/2004 | 29 | 62 | 67 | Clear day |
| 06/08/2004 | 30 | 66 | 68 | Clear day |

(*continued on next page*)

Table 4 (*continued*)

| Date | Cold water temperature (°C) | Hot water temperature (°C) | | Remarks |
|---|---|---|---|---|
| | | Plain heater | Finned heater | |
| 07/08/2004 | 31 | 64 | 65 | Clear day |
| 08/08/2004 | 32 | 58 | 58 | Rainy day |
| 09/08/2004 | 26 | 53 | 56 | Overcast day |
| 10/08/2004 | 28 | 63 | 65 | Clear day |
| 11/08/2004 | 31 | 53 | 56 | Clear day |
| 12/08/2004 | 29 | 66 | 68 | Clear day |
| 13/08/2004 | 28 | 67 | 70 | Clear day |
| 14/08/2004 | 28 | 67 | 69 | Clear day |
| 15/08/2004 | 28 | 64 | 70 | Clear day |
| 16/08/2004 | 32 | 54 | 64 | Forenoon clear, then overcast |
| 17/08/2004 | 28 | 42 | 43 | Rainy day |
| 18/08/2004 | 25 | 53 | 54 | Overcast day |
| 19/08/2004 | 28 | 56 | 58 | Clear day |
| 20/08/2004 | 28 | 47 | 48 | Forenoon clear, then overcast |
| 21/08/2004 | 28 | 65 | 65 | Clear day |
| 22/08/2004 | 30 | 49 | 50 | Rainy day |
| 23/08/2004 | 26 | 59 | 62 | Clear day |
| 24/08/2004 | 27 | 55 | 61 | Forenoon clear, then rainy |
| 25/08/2004 | 26 | 52 | 60 | Forenoon clear, then overcast |
| 01/09/2004 | 28 | 67 | 67 | Clear day |
| 02/09/2004 | 27 | 60 | 70 | Clear day |
| 03/09/2004 | 28 | 64 | 67 | Clear day |
| 04/09/2004 | 28 | 64 | 67 | Clear day |
| 05/09/2004 | 28 | 65 | 69 | Clear day |
| 06/09/2004 | 26 | 65 | 69 | Clear day |
| 07/09/2004 | 27 | 68 | 70 | Clear day |

has a better opportunity to transfer heat. However, the thickness of the fin has an important bearing on this energy transport as shall be shown presently.

Starting from the fin temperature distribution equation for the assumed boundary conditions of heat loss from the fin tip being negligible, it may be shown that

$$\frac{T - T_\mathrm{w}}{T_\mathrm{b} - T_\mathrm{w}} = \frac{\cosh m(L - x)}{\cosh mL} \tag{1}$$

Fig. 7 shows the temperature distribution of the fin for the present construction, i.e. fin thickness = 1 mm. Due to the narrow cross-sectional area available it is noted that a sharp temperature drop occurs within a short distance from the top. In fact a 95% temperature drop occurs within the top 22.5 mm. Thus, we may conclude that, realistically speaking, only the top 22.5 mm (or a quarter of the fin) is effectively transporting heat to the water body. If a thicker fin is used it would obviously enhance the thermal characteristics of the extended surface and this effect is explored in Fig. 8. Within the latter figure, the fin length across which a 95% temperature drop occurs is shown for varying fin thickness. Note that for a thickness of 8.5 mm the entire fin would participate in the heat transport mechanism.

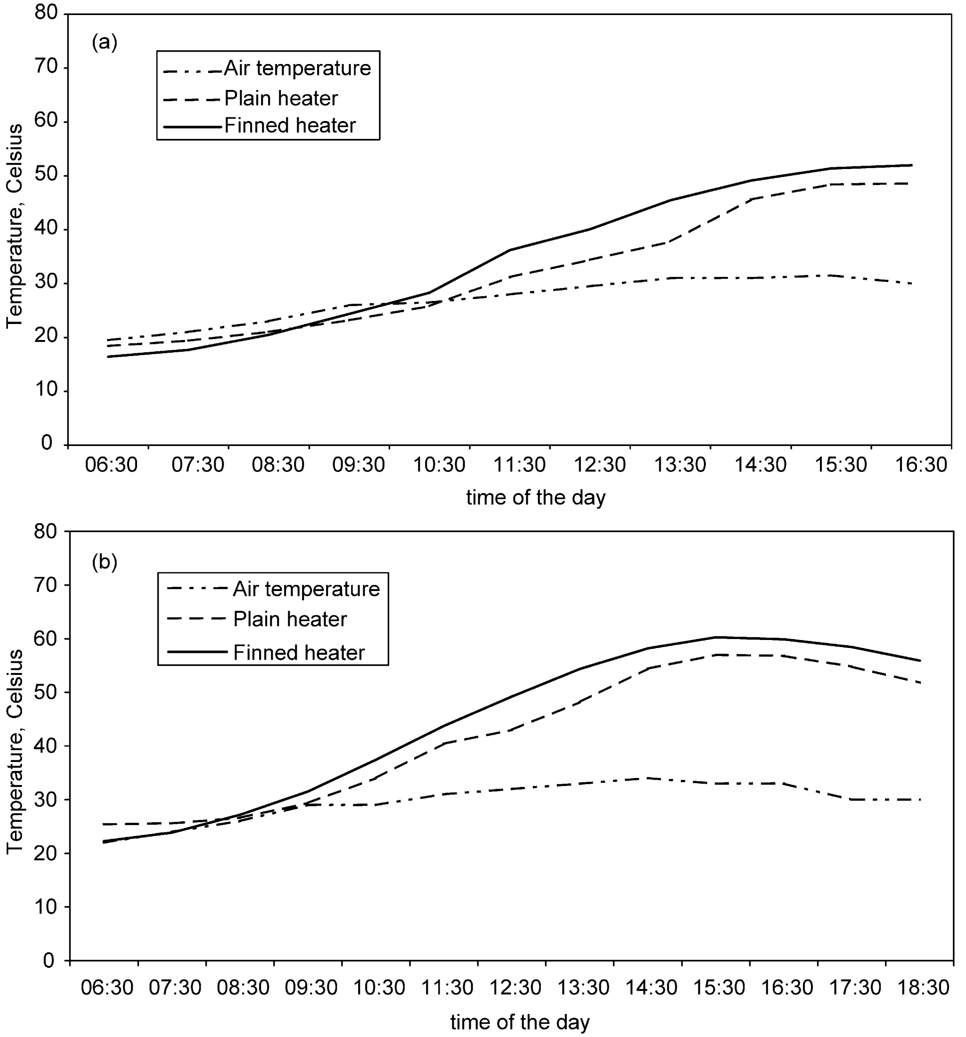



Fig. 5. Average water temperature for plain and finned heaters: (a) clear day (May 2, 2004) and (b) overcast day (May 1, 2004).

However, the monetary cost, embodied energy within the thicker fin and life cycle related issues would be prohibitive for such a design.

We return to the question that despite its apparent low direct impact on thermal transport, the finned heater as shown above has a much better experimental performance. The answer is provided via computational fluid dynamic (CFD) work that was presently undertaken. Fig. 9 shows the temperature (a) and velocity (b) raster plots for the sectional area between two adjacent fins. Fig. 9(a) confirms the above reported analysis that only a quarter of the fin length is effective. This is shown by a lack of change of colouring (web version only) within the bottom three-quarter fin height. Fig. 9(b) is, however, most

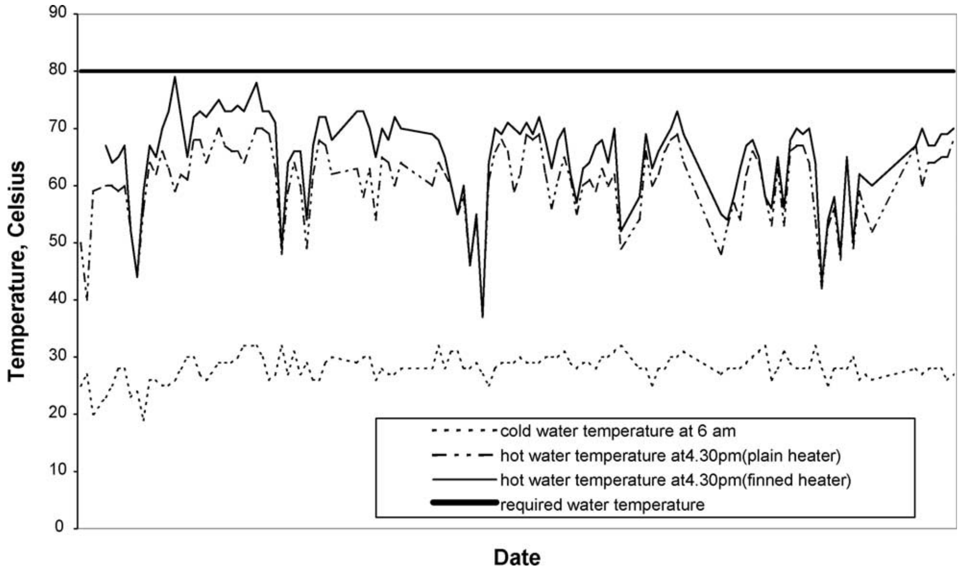



Fig. 6. Temperature lift for plain and finned heaters.

interesting. The altered flow structure due to the presence of the fins is the key to the thermal enhancement of the finned heater. As is clearly shown in Fig. 9(b) a significant body of water has motion induced within it and is thus brought in intimate contact with the top absorber plate. As a matter of fact it is also possible to work out the optimum fin spacing for the present construction. This optimum spacing would require that there would be no quiescent zone at the top end of the cross-section, i.e. the plumes issued from the two

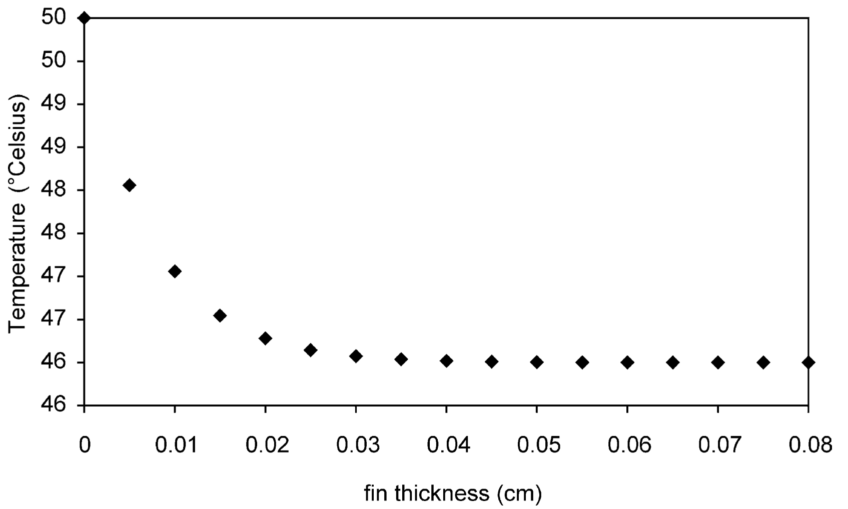



Fig. 7. Temperature distribution along fin length.

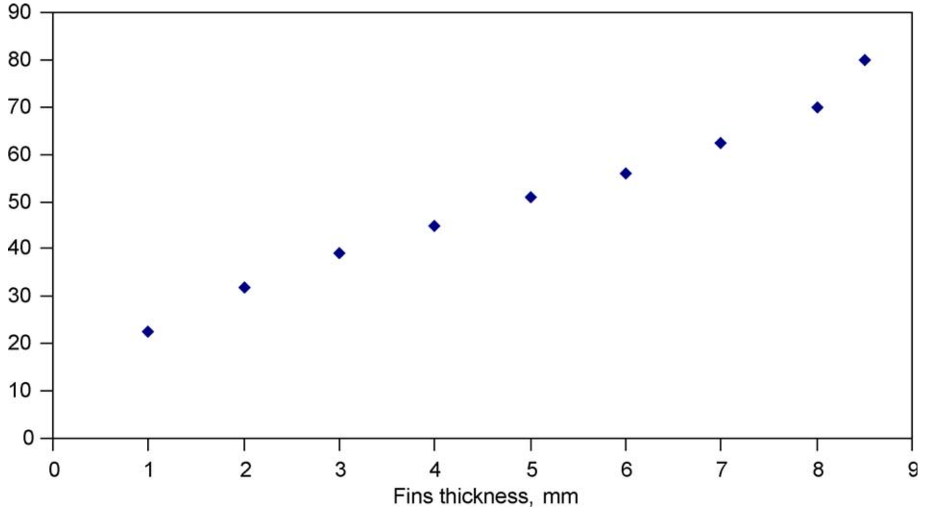



Fig. 8. Fin length across which a 95% temperature drop (from the fin top to its bottom) occurs.

vertical ends would just touch each other. In the present case, the optimum spacing works out to be 166 mm.

### 5.4. Discussion

The basic method of measuring solar thermal flat-plate collector performance is to expose the operating collector to solar radiation and measure the fluid temperatures and fluid rate. These data permit the characterisation of collector by parameters that indicate how the collector absorbs energy and how it loses energy. Standard test procedures are available for liquid heating collectors and these have been developed by ASHRAE [10].

The result of the above test may then be used to obtain the efficiency plot for the collector expressed as function of $(T_i - T_a)/I_T$ parameter. Note that $T_i$ and $T_a$ are, respectively, fluid inlet and ambient air temperatures and $I_T$ is the irradiance on collector plate.

For the Pakistani locality under discussion (Bhai Pheru) where the present measurements were undertaken no solar irradiance data were however available. As a matter of fact measured data set for even the principal conurbations of Pakistan for the past several years are unavailable owing to respective stations being shut down. The only location where any global irradiance is currently being measured is Quetta. In view of the above difficulty, precise estimates of thermal efficiencies of the two heaters designs—plain and finned type are not feasible. Using the results obtained from tests conducted by the present lead author on thermosyphon and built-in-storage (plain design) heaters [11,12] and using the presently available test data a set of abbreviated efficiency figures were obtained, these efficiency estimates are shown in Table 5. Note that the climatic conditions for principal Pakistani location are inter-compared with those for Benghazi,

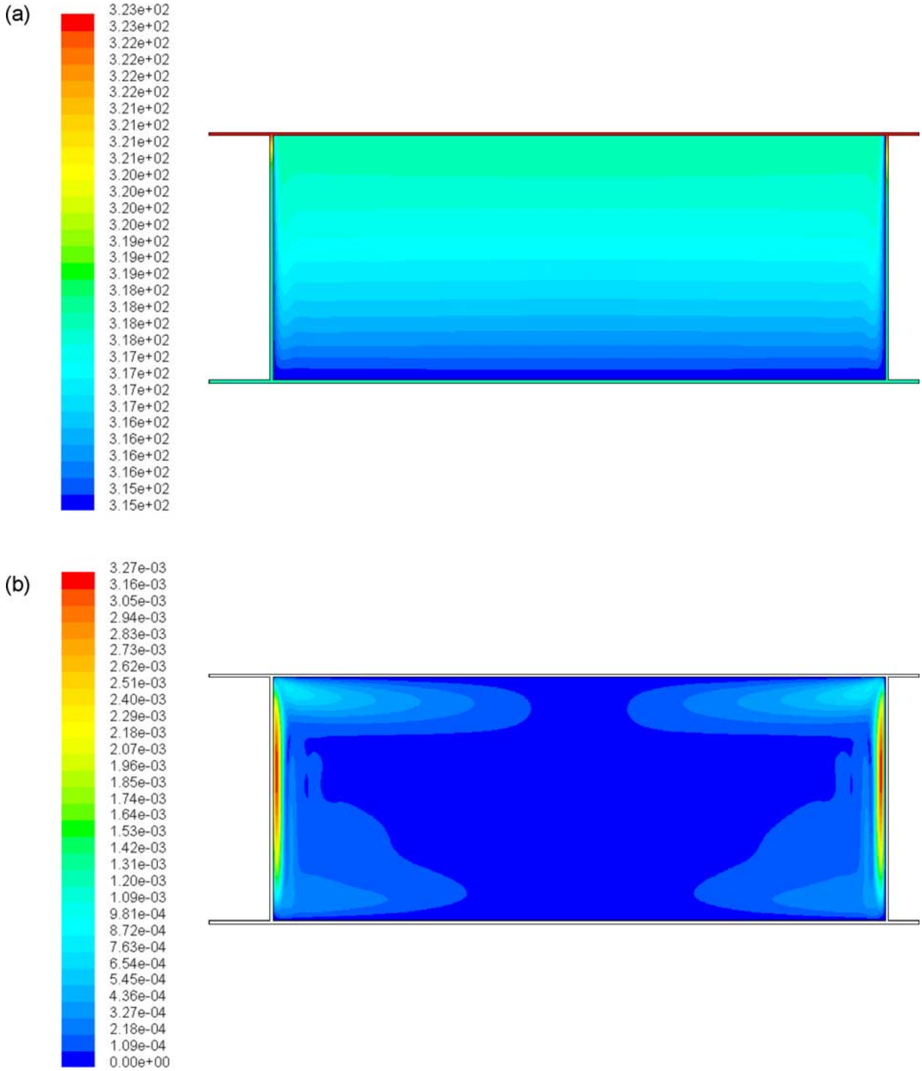



Fig. 9. CFD raster plot for finned heater: (a) temperature distribution and (b) velocity magnitude (m/s).

Libya (Tables 5 and 6), where more detailed efficiency tests were undertaken on thermosyphon and built-in-storage heaters [11].

## 6. Economic and LCA issues

The total cost of manufacturing the two heaters—plain and finned types—were, respectively, Pakistan Rupees 7000 and 7500. These costs are, respectively, equivalent to US$112 and 120. Note that the Chinese 'Nanjing HDE solar energy technology company'

Table 5
Efficiency estimates (%) for the three types of solar water heaters that are suitable for developing countries

| Design type | Average efficiency | Ref. |
|---|---|---|
| Thermosyphon | 40 | |
| Built-in-storage: plain | 47 | |
| Built-in-storage: finned | 55 | Present work |

is actively seeking sales outlet in Pakistan for their thermosyphon type solar water heaters. The latter cost Rupees 18,000 (US$288).

Furnace heating oil (the primary fuel for water heating employed within the textile sector in Pakistan) costs US cents 2.0/kW h. It may also be noted that electricity costs are US cents 3.2/kW h. The total cost for water heating using furnace oil thus works out to be US cents 44.3/l/annum. Note that the reported performance of the two heaters was undertaken for only a 3-month period (21 April to 20 July, 2004). This was owing to the rather limited availability of funds for the present study. The overall annual-mean efficiency of the heaters was, however, estimated based on the annual average irradiation and ambient temperature (Tables 3, 5 and 6). Using the efficiencies reported in Table 5, the respective annual savings work out to be US$16.7 and 19.6, respectively, thus giving a simple payback period of 6.7 and 6.1 years for the plain and finned heaters.

Solar energy is a renewable form of energy that does not have any direct environmental impacts. There are, however, environmental burdens associated with solar water heaters due to the materials used and the fabrication that is involved. The environmental consequences of these transactions include natural resources depletion, greenhouse gas emissions and acid rain. It is therefore necessary to evaluate the indirect environmental impacts caused by the solar water heaters. Life cycle assessment (LCA) is a very helpful tool in this regard that not only provides an account of materials and energy involved in a product or system but it also measures the associated environmental impacts.

Life cycle assessment is defined as: ‘A process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively or qualitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of the energy. The assessment includes the entire life cycle of the product or activity, encompassing, extracting and processing the raw materials: manufacturing; distribution; use; reuse; maintenance; recycling and final disposal; and all transportation involved [13].

Generally, there are four interactive steps necessary for a complete life cycle study: Planning, Inventory analysis, Impact assessment and Improvement analysis (see Fig. 10).

Table 6
Comparison of dry-bulb temperatures for Pakistan and Libya (°C)

| | Lahore | Karachi | Benghazi, Libya |
|---|---|---|---|
| Winter | 3 | 11 | 9 |
| Summer | 42 | 37 | 34 |
| Latitude (degrees) | 31.6 | 24.8 | 32.1 |

Winter refers to 97.5% design temperature, summer to 2.5%. Source: ASHRAE [10].

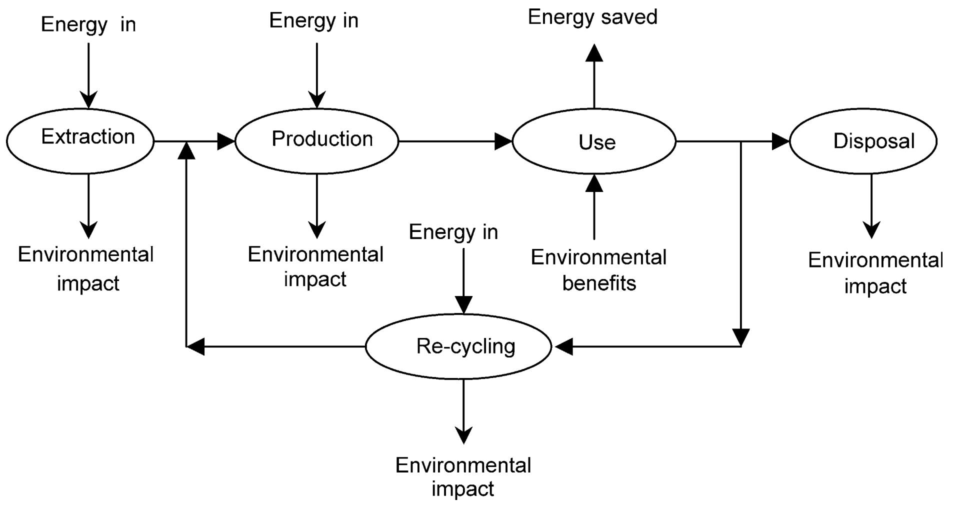



Fig. 10. Diagrammatic sketch of the LCA procedure.

Results of any LCA study are always dictated by the planning phase, which defines the goals, objectives and investigation boundaries of the framework. The results also depend upon the inventory analysis that is undertaken. For example, the environmental impacts associated with energy consumption may vary from country to country depending on modes of energy used, i.e. thermal, nuclear, or renewable.

The LCA investigations carried out for the presently designed solar water heaters cover embodied energy and environmental impacts associated with construction of these heaters. Estimates for the total embodied energy of materials involved have been determined. The value for the energy consumed during manufacture of heater is not included in this investigation. There are five types of materials involved in the construction of solar water heaters. They are: stainless steel, glass, timber, glass wool insulation and rubber. Based on embodied energy figures for the respective materials provided by Berg [14] and Buchanan [15], total embodied energy for the manufacture of solar water heaters has been estimated. Environmental impacts associated with the heaters have been expressed in terms of carbon generated by each material during its production. Table 7 summarises the results of embodied energy and environmental impacts estimations for the plain and finned heaters.

Table 7
Life cycle assessment for the solar water heaters manufactured and constructed for this study

| Material | Quantity (kg) | | Embodied energy (MJ) | | Carbon released (kg) | |
|---|---|---|---|---|---|---|
| | Plain | Finned | Plain | Finned | Plain | Finned |
| Stainless steel | 30 | 33 | 1050 | 1155 | 18.30 | 20.13 |
| Glass | 11 | 11 | 340 | 340 | 6.70 | 6.70 |
| Glass wool | 2 | 2 | 40 | 40 | 1.75 | 1.75 |
| Rubber | 0.1 | 0.1 | 15 | 15 | 0.28 | 0.28 |
| Timber | 20 | 20 | 44 | 44 | 0.8 | 0.8 |
| Total | | | 1489 | 1594 | 27.9 | 29.7 |

Here it must be noted that the plain heater requires less steel than finned heater due to which its overall embodied energy is less. Each of the presently discussed experimental prototype heaters heats up 80 l of water and the total energy requirement to heat that body of water to 80 °C is 17.13 MJ. Using the efficiency figures provided in Table 5 the respective embodied energy payback period for the two heaters are therefore 185 and 169 days.

## 7. Conclusions

The present work proposes the introduction of built-in-storage water heaters for Pakistani textile industry due to its low cost and simple construction as compared to thermosyphon heaters. A new design has been adopted within built-in-type heaters by introducing fins within its construction. Fins not only improve the thermal efficiency of the heater but also add to the structural stability of heater—fins joined to the top and bottom layers of heater can provide additional strength against hydrostatic forces and can help overcome the bulging problems that usually arise in such designs. in the present work both of these heater designs—plain and newly designed finned type—were constructed to compare their thermal performance.

Three months of experimental data were collected for the two heaters—plain and finned types. The solar fractions for this period were found to be 63 and 73%, respectively. The monetary and embodied energy payback periods for the two heaters were, respectively, found to be 6.7 and 6.1 years, and 185 and 169 days.

## Acknowledgements

The authors would like to acknowledge the enthusiasm of Messrs Mian Munir, Mian Nasir and Mian Naveed of Din Textile Group for initiating the present programme of work. The authors are also grateful to Napier University for the loan of measuring instruments that were used for determining the performance of the solar water heaters at Din Textile Mills, Bhai Pheru, Lahore, Pakistan. The authors are also thankful to the staff at the latter concern that diligently recorded all temperatures and sky observations that are presented in this article.

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